POLLEN ANALYSIS OF GLACIERS IN SPECIAL RELATION TO THE FORMATION OF VARIOUS TYPES OF GLACIER BANDS

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Paper read at a Meeting of the Society on 5 February 1949

ABSTRACT. The author describes the work of Dr. V. Vareschi on the pollen content of glacier ice. A general account of the method of analysis is given. The results of statistical evidence of the analyses on several alpine glaciers are discussed, particularly in regard to the general nature of glacier flow in different parts of the glaciers. Vareschi's suggestions as to the modes of origin of a certain type of ogive banding and of parallel banding (*Pflugfurcheneis*) are dealt with in the light of his findings. It is pointed out that what appears to be a valuable new approach to the solution of glacier flow problems needs elaboration before it can be accepted in all its bearings.

ZUSAMMENFASSUNG. Der Verfasser beschreibt Dr. V. Vareschis Arbeiten über den Pollengehalt in Gletschereis. Ein allgemeiner Bericht der Analysen Methode ist wiedergegeben. Die Resultate statistischer Beweisführungen von Analysen mehrerer Alpengletscher werden besprochen, besonders in Hinsicht auf die allgemeine Beschaffenheit der Gletscherströmung in verschiedenen Teilen der Gletscher. Vareschis Vorschläge die Art des Ursprungs gewisser Ogiven und betreffend Pflugfurcheneis, werden mit Hinblick auf dessen Untersuchungsergebnisse behandelt. Es wird betont, dass, was eine wertvolle neue Annäherung zur Lösung von Gletscherströmungs–Problemen zu sein scheint, sorgfältiger Ausarbeitung bedarf, bevor es in jeder Beziehung acceptiert werden kann.

DR. VOLKMAR VARESCHI, who came from Munich to work in the Geobotanical Institute (Geobotanische Forschungsinstitut Rübel) in Zürich, published from there in the years between 1935 and 1942 a series of articles upon his investigations of the pollen content of glacier ice, and especially upon their application to our knowledge of glacier structure and our theories of glacier movement. No other investigator appears to have entered this field of research, and it is entirely with Vareschi's work and ideas that I am now concerned.

Not only snow, hail, and rain fall upon the great glacier fields, but also a great deal of dust, and with it a vast amount of pollen blown in from the surrounding plant-clothed countryside. Vareschi has shown how this pollen can be recovered, identified, and related to its sources. In particular he has demonstrated that as the composition of the pollen rain changes throughout the year with the successive flowering of various plant species, so in the thick annual increment of snow upon the upper firn, the annual procession can be recognized in the pollen types preserved.

Pollen grains are released from the sporangia of flowering plants and coniferous trees, and being small (between 10 and 100 microns in diameter) often travel great distances before settling to the ground. Although wind-pollinated plants, such as the majority of European trees, grasses and sedges, constitute the main source of air-borne pollen, considerable amounts also come from insect-pollinated species. When viewed beneath the microscope the grains are seen to have numerous characteristics of size, shape, pore-number and character, wall-thickness and sculpture, which permit identification to the degree of genus in most instances, and even to species in others. These facts of course lie behind the technique of pollen-analysis which has been so extensively applied to investigations of quaternary history, hay-fever, and the origin of honey.

Vareschi's field method is to remove the surface ice and clean the face of a suitable crevasse, and after making notes of the stratigraphy of the ice, to cut out from 2 to 10 cubic dm. of uniform ice, melt it on a Primus stove and hand-centrifuge the melt-water, transporting the muddy residue to the laboratory in collecting vessels with some preservative such as thymol. In the laboratory the centrifugate is treated with strong hydrofluoric acid to remove mineral residue, and the remainder is mounted in glycerine on slides for examination. The counts can be made quantitatively, and amounts of pollen are found up to 5000 pollen grains per cubic dm. of ice. Together with the pollen there are also abundant organic remains of all kinds, but so far these have not been made the subject of analysis.

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Vareschi made his first investigations on the firn of the Great Aletsch Glacier and compared the pollen content of the surface ice with the composition of the forests in the surrounding area of 2000 sq. km. A remarkable degree of correspondence was shown. He was also able to show that the spectral composition of the ice from different glaciers is characteristic if they are compared at equivalent seasons. In the Aletsch region the flowering times of species contributing to the pollen rain extend from March to August, with the hazel and alder early, pine and spruce succeeding in the summer, with the winter lime and *Pinus cembra*, the five-needled pine, as the latest.

On the Gepatsch Glacier of the western Ötztal Alps, Vareschi pursued his investigation of the relationship of this seasonal drift to ice layering. Samples were taken from three sites: the highest, at 3080 m., was in the centre of the firn; the middle, at 2780 m., was just above the ice-fall at the head of the glacier tongue; the lowest, at 2150 m., was in the tongue itself in the ablation region.

Samples taken from the highest site, where the ice was conspicuously banded, had a very different pollen content in the succeeding layers (Fig. 1 below). Some had a low pollen frequency and spring-flowering species only, others with high pollen frequency, summer-flowering trees and abundant grasses and flowering herbs, were clearly formed in mid-summer, whilst winter ice had

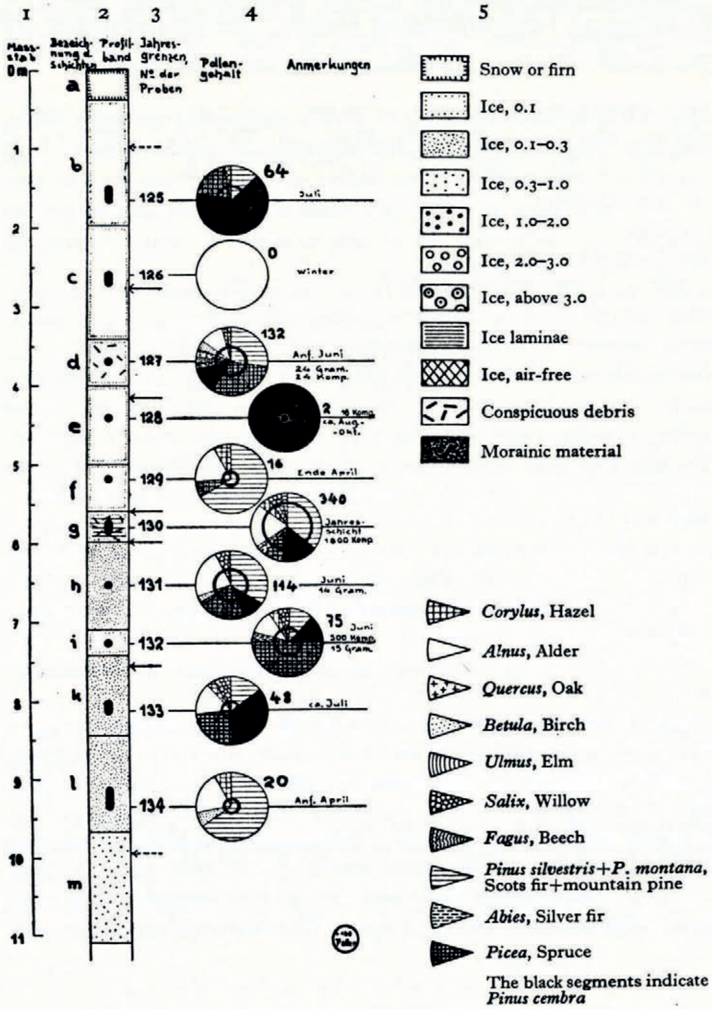

Fig. 1. Profile from the Gepatsch Glacier at 3080 m.

Col. 1 shows scale in metres

Col. 2 represents the characteristics of the ice layers recognizable in the crevasse face; the key is in Col. 5, the grain sizes, in centimetres, being approximate. The black dots show the positions from which samples for analysis were taken

Col. 3. The arrows indicate the limits between the snow of successive years as indicated by the pollen analyses. The sample numbers are shown in heavy type

Col. 4. The clock-face diagrams show the pollen content, the heavy outline circle of which is proportional in area to the absolute tree pollen frequency. The proportions in which different types of pollen occur are indicated by the sizes of the various sectors, differently shaded (key in Col. 5). In general the early flowering species have a pale grade of shading; the latest flowering are darkest. Note the clarity of the distinction between the samples in the yearly aspects they severally represent. Spring and summer aspects preponderate

(See Zeit. Gletsch. Bd. 23, 1935, p. 271)

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almost no pollen in it. There was little relation between season of formation and the banding characters of ice grain size, colour and thickness. But certain bands of laminated dirty ice showed prodigious pollen frequencies without clear seasonal aspect (both early and late season pollen mixed together), and were evidently the result of melting of the ice formed throughout an entire season. It was possible by considering the results from a vertical series of samples to infer the progress of accumulation at the site through several years.

From the middle site similar results were obtained, although the mean annual thickness of ice seemed less than in the high firn.

At the lowest site, below the fracture zone, seasonal aspects and the annual layering were no longer recognizable.

It would seem from these results that whilst in the firn a type of movement prevails which preserves the horizontal aspect layering, in the glacier tongue this is replaced (or supplemented) by a smaller scale differential movement which effectively mixes the layers. Vareschi points out that one must beware of interpreting the results as if the results from the three sites represented a true time sequence. The layers formed in the high firn are thick and have the full seasonal range of aspect, but at lower sites these layers are buried and the accessible surface layers have formed in conditions of lower altitude leading to melting of summer layers, partial merging of aspects, or perhaps to fusion of the whole year's snowfall.

In 1937 the investigations moved to the Clariden firn, where since 1926 Dr. Streiff-Becker had taken observations from a snow-gauge of the accretion and ablation on the firn. The site was at 2700 m., only 50 m. above the firn line, a circumstance strongly reflected in the history of the ice formation. The correspondence between the observed periods and depths of snow accretion was very close. A stained ice layer representing four years' increment had the typical absence of seasonal aspect but very high pollen frequencies, thick layers of winter snow were recognizable by their very low pollen content, and in places the pollen showed the seasonal progression fully. At one level an ice-lens due to local melting in the autumn was seen to have a concentration of pollen as expected. Possibly of the greatest interest was the observation that the ice just below a heavy layer of concentration retained its low pollen content and clear seasonal aspect, thus showing that pollen grains do not percolate to lower levels through hair cracks in the ice, although fine mineral particles may do so.

Gratifying as these results are, it will be noted that there is no means in the pollen examination itself of saying how long any of the gaps should be taken to represent, and it is possible that the products of a period of melting may indeed be drained away altogether.

Vareschi's latest and most important researches were made upon various systems of banding which appear in the tongue of the Great Aletsch Glacier, in particular what are locally called *Ogiven*. These are curved bands visible on the glacier surface, often in regular longitudinal series. They are best seen from a distance, and on the Great Aletsch, a glacier of moderate and even gradient, they have been often observed, photographed and recorded. They there fall into separate parallel series, each related to ice coming from a distinct ice field. The ogive itself is generally of darker block ice, whilst between one ogive and the next is paler and higher *Buckel* ice (see Fig. 2, p. 328 and Figs. 3 and 4, p. 333).

Pollen investigation shows that the dark ogive ice has summer, spring and autumn aspects, whilst the paler intermediate regions have winter ice only. Moreover samples in sequence from the glacier snout upwards across a single ogive regularly show the correct seasonal sequence of aspects. It would therefore seem probable that the ogives are the original firn layers, more or less undisturbed since deposition, and here revealed by ablation. The curved form is regarded by Vareschi as due to curvature of the layers in conformity to the shape of the valley floor. If the ogives are in fact the transected layers of the firn, this fact should be clear from analysis of vertical profiles in the ogive region, and indeed full yearly cycles can be so demonstrated.

The ogive structure thus revealed was similarly shown to exist in the ogives of the Konkordiaplatz, and of the Gepatsch Glacier.

Between each of the parallel ogive systems in the Aletsch Glacier there is a belt of *Pflugfurcheneis* (Reid ridges or parallel bands) in which long tabular ridges of ice of varying height run parallel with the glacier axis. Pollen samples taken from along the length of any one band always show the same seasonal aspect, but series taken transversely across several bands, although disclosing many contrasting seasonal aspects, show no regular seasonal sequence, but only a fortuitous one. It is concluded that the movement here is quite different from that in the ogive region of the glacier tongue, and although more or less parallel with the seasonal bands, it is not concerned with differential moving of very small units (see Figs. 5 and 6, p. 333).

In the glacier snout itself, and at the margins of the glacier next to the valley sides, there occurs a third type of ice, which upon examination proves to have no seasonal aspect differentiation at all. It seems that in this ice, which comes from the regions of greatest pressure, the scale of differential movement is finer than elsewhere.

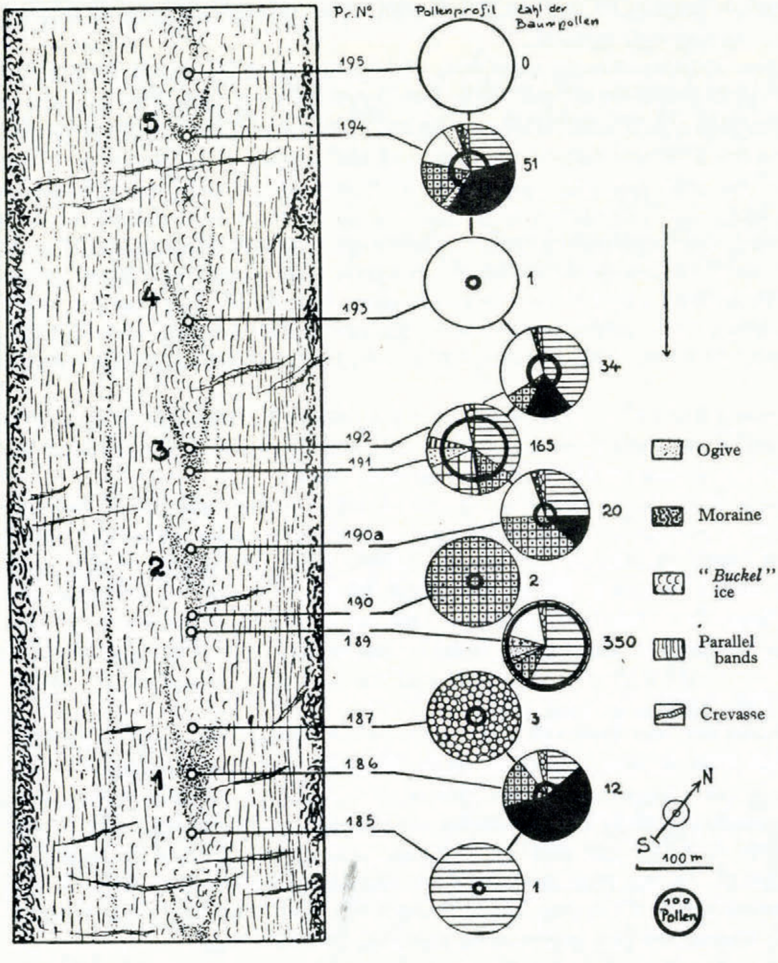

Fig. 2. Sketch-map of part of the Jungfrau component of the Great Aletsch Glacier, showing its ogive system and the results of pollen analyses made from surface ice samples taken at the indicated places. The convention for representation of the absolute tree pollen frequency, and the relative frequency of the different types, is the same as that in Fig. 1 where the key will be found. Samples taken between the dark ogive bands are typical winter ice with low pollen content. Samples from the ogive bands themselves have a high pollen content and spring, summer or autumn aspects. In certain instances within one ogive (e.g. samples 189, 190, and 190a) the aspects follow the proper seasonal sequence; note the alder-pine dominance in the first, the spruce in the second, and the high spruce with Pinus cembra *(with which lime is associated) in the third*

(See Geob. Inst. Rübel, Vol 19, 1942, p. 91)

Vareschi stresses that the pollen investigations show the character of the glacier movement rather than point directly to any particular mechanism of it. All the same he points out how in large degree his results conform to various parts of the hypotheses of Philipp and Finsterwalder. He considers that his findings agree with the views of Finsterwalder on the distortion of areas between the firn and the glacier tongue, and with Finsterwalder's hypothesis of the course travelled in the vertical plane, according to which snow deposited highest on the firn comes out lowest on the glacier snout. It is indeed difficult to account for the regular seasonal structure of the ogives except upon a theory essentially of this character.

Whilst these results come from work which is as yet in an early and tentative stage, present features which are still unsatisfactory and are applicable to a limited number of glaciers only, nevertheless they have to be accepted as giving a systematic body of facts which will have to be taken into account in theories of glacier movement.

Certain criticisms and queries naturally present themselves. One wonders why samples have been always chosen from the *centre* of the recognizable ice layers, and whether there would not be great advantage in working with continuous samples throughout a profile, so as to reveal the *full* history of the deposit.

In the intermediate Gepatsch profile (as in other places also) there is a very remarkable lack of winter ice layers, and one wonders whether winter snow was ever present in this sequence. It would be remarkable indeed if the snow were consistently of spring and summer origin, but that is what the analyses suggest. If it is not so, then it is clearly of great importance to learn how the winter ice has disappeared, and whether winter ice can in fact vanish progressively with time and passage down the glacier leaving other layers intact.

One wonders how the presence of particles such as pollen grains, in very different frequencies in different layers, may affect the recrystallization of the ice, and indeed the development of minor slip-planes in the glacier—matters susceptible to both theoretical and experimental treatment.

Useful as the recognition of seasonal aspects has become, it has not hitherto been possible to recognize characteristic sequences in the profiles which might serve to date exposures of bands, and it is perhaps too much to hope for this. All the same, widespread disforestation or afforestation might give time indices recognizable in deeper glacier layers.

No working pollen analyst can fail to be impressed by the thought of the countless numbers of pollen grains from the melting glacier, swept down the rivers to the sea, or to incorporation in the archives of lake-bottom muds, and so Quaternary history finds itself also related to these glacier investigations.

It is much to be hoped that Vareschi will himself resume research in this field and that his work will also be checked and extended by new workers in fresh glacier regions where other conditions may well afford different opportunities.

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DISCUSSION

The CHAIRMAN (Professor F. Debenham) opened the meeting for discussion.

Mr. G. SELIGMAN: In his address, which I can only describe as a brilliant exposition of a difficult subject, Dr. Godwin has clearly shown us the nature of two types of glacier banding, the rounded ogive bands which lie horizontal and are the remains of the original snow stratification, and the vertical bands which still show some stratification, but whose strata have been disturbed from their original sequence—the Parallel Bands. The latter nearly always occur when a glacier narrows or receives a tributary, and are therefore believed to be due to lateral pressure.

An American member of this Society, Mr. Joel E. Fisher, who is interested in ogive banding, has asked me to make a communication on his behalf. He, like Vareschi, believes that the type described by Dr. Godwin has maintained its original stratification and has become visible owing to the strata having been truncated by the conical melt surface of the glacier. He calls these bands "Alaskan" as he believes them to be more common in that region than in the Alps. But he believes that there is another type of banding, which, although exhibiting the same superficial characteristics, is formed in an entirely different way. These he calls "Forbes's bands" after their original discoverer (see Figs. 3 and 4, p. 333). Mr. Fisher writes:

"The mechanism of their production is a seasonal block-faulting off of large glacier-wide islands of *névé* at the head of the ice fall, which ride down through the entire ice fall as solid blocks of compact *névé*, while between these solid islands is a breccia of broken ice and surface snow which, consolidating into ice under less strenuous conditions than prevailed in the upper *névé*, produces at the bottom of the ice fall an ice which is more aerated. Such alternating vertical structures, created in the ice fall, riding on down the outrunning valley glacier under pure gravitational glacier flow, always retain their vertical structure."

Mr. Fisher also cites Professor W. Bucher, President of the American Geophysical Union, as agreeing with his view that Vareschi's analysis cannot be applied to the "Forbes's" type as shown by bands on the Mer de Glace and some other alpine glaciers.

Nevertheless I do not think that we are yet in a position to accept Mr. Fisher's views as final. Dr. Streiff-Becker believes that the bands are formed as the result of strong pressure below an ice fall which increases the plasticity of the ice. If at the same time the ice is dammed up at this point by a narrowing of the glacier bed, waves are formed in the ice and dust collects in the troughs. Hess on the other hand believes that dust collects in the crevices between blocks in an ice fall and the blocks closing together show the former fracture as bands. Clearly the first need is to establish the exact crystalline structure of these bands.

If indeed there are two types of these bands which look so much alike, we shall have to reconsider our nomenclature and it might be well to call them generically "ogives" subdividing them into Alaskan and Forbes's bands. There are of course many other types of glacier bands but they do not come into our purview to-day, although it is high time that a thorough study of all glacier bands should be made.

Mr. W. V. LEWIS (Department of Geography, Cambridge): May I say at once how welcome is this most promising application of the technique of pollen analysis to the tracing of the movement of ice in a glacier.

A point which puzzled me was the apparent scarcity of ice deriving from winter snowfall in the samples analysed. Very little spring or summer snowfall would normally survive the summer melt and contribute to a glacier's mass which, in the main, must derive from winter snowfall. The evidence of seasonal snowfall forming the ogives seemed convincing, but here again the proportion of dirty "summer" ice to "winter" ice seemed unaccountably high. Might this not be due, in part, to the downward seeping melt-water carrying the pollen grains with it?

Also was there direct evidence that the dirty bands in the ogives continued back into the glacier so as to show horizontal stratification?

Dr. Godwin: I agree that the apparent deficiency of ice of winter origin is the most suspicious feature of the profile analyses, and it is on this account especially that further work and more intensive sampling is called for. So far as I know, there has been no tracing of the ogive bands backwards into the firn and this would presumably be difficult, and would call for a means of distinguishing particular bands which we at present lack.

Mr. J. N. Jennings (University College, Leicester): Although pollen downwash in peat deposits has been demonstrated to be a negligible source of error, it would seem that melt water percolation through the network of interstices in firn might be a likely factor in carrying pollen downwards to accumulate the grains at a blue band. Has Vareschi clearly eliminated the possibility of this being an important process and shown that this consideration could not solve some of the difficulties of interpretation of the pollen profiles?

Dr. Godwin: Although the evidence quoted seems to exclude the movement of pollen along hair cracks in the ice, the details of melt phenomena and regelation in the neighbourhood of the firn line clearly do call for much more investigation. For example snow melting from surface ridges might lead to sedimentation of pollen in corresponding surface pools.

Professor G. Manley (Bedford College, London): Can Dr. Godwin tell us whether the pollen can be regarded as fairly representative of the trees in the neighbourhood of the glaciers? Given a few very windy days, for example in the spring, was there not a chance that pollen might derive from more distant lowlands?

Dr. Godwin: On the whole the glacier pollen content closely represents the forest vegetation of the neighbourhood, but certainly pollen is also borne in from greater distances, and Vareschi in fact describes the function of certain valley winds in such transport. No effective account of this distant pollen has so far been made.

Mr. W. H. Ward (Building Research Station, Watford): Dr. Godwin showed a picture of the broad transverse banding on Austerdalsbreen in Norway that I took in 1938. He expressed some doubt with regard to the similarity of these bands to Vareschi's ogives. There has been much confusion about glacial banding, because there is more than one type of band and it is sometimes difficult to know which type is being described. When walking up the easy slope of Austerdalsbreen I had never seen any bands before and, not expecting them, I only noted changes in the "blueness" of the ice. Close examination of the photograph shows that both light and dark bands are subdivided into many fine bands.

Last summer (1948), again by accident, I observed from a distance identical broad bands below the ice fall on Tvarbreen, a small glacier that, like Austerdalsbreen, also discharges from Jostedalsbreen. Close examination of the broad bands showed that:

(1) They are subdivided into fine parallel transverse bands. Adjacent fine bands vary appreciably and irregularly in thickness.

(2) The crystal size of each fine band is characteristic but varies appreciably and irregularly from band to band. The mean size of the crystals decreases with altitude.

(3) The fine bands dip regularly at varying angles into the glacier to the full depth of open crevasses and extend transversely right across the glacier.

(4) The fine bands persist through the icefall and similar bands are visible in the *névé*.

(5) The fine bands collect on their lower exposed edges small quantities of organic and mineral matter which tends to produce differential melting and accentuates their surface profile. The way in which these fine bands are grouped together to form a broad dark or light band when seen from a distance, was not established. I cannot conceive that the broad dark bands, being composed of

hundreds of fine bands, are annual—the scale is all wrong. They cannot correspond to Vareschi's ogives, which seems to confirm Mr. Fisher's view that two distinct ogive types exist. The plough-furrow (parallel-banded) structure described by Vareschi and illustrated by Dr. Godwin from a picture taken by Mr. Seligman seems to be similar to the fine Norwegian bands. Curiously enough they run in orthogonal directions.

The CHAIRMAN: The hour is growing late and I must bring the meeting to a close. It has been very interesting to hear of yet another application for pollen analysis, for which we have to thank Dr. Godwin as a result of his many years of work in that line. The only comment I have to make on the problem of banding is that the belts towards the side of the glacier, where the banding is nearly vertical and in the direction of flow, might be explained as follows: since bands of this kind are seasonal and move downwards and outwards under the pressure of succeeding layers, it would be natural to expect that towards the side of the glacier they would be tilted upwards to an even more marked degree than towards the snout of the glacier.

In your name I thank Dr. Godwin most heartily for his excellent paper.

The meeting then terminated.

ICE MARGIN FEATURES, LEIRBREEN, NORWAY

By G. DE BOER (University College, Hull)

AN interesting set of ice margin features, including shoreline terraces and an overflow channel recently deserted by the waters of a glacier-dammed lake, was seen in September 1947 during a field meeting of the Cambridge University Department of Geography in the Jotunheim district of Norway.

About 2 km. east of Krossbu, in the western part of Jotunheimen, and at an altitude of about 1500 m., a broad rocky spur projects into Leirbreen. The terraces lie on the southern flank of the spur where a lobe of ice had held up a lake in the lower part of a wide, shallow gully (see Fig. 4, p. 335). Two well marked shore terraces, and a number of lesser ones, showed that the lake had emptied in several stages (Fig. 1, p. 334). The two main terraces—depositional features composed of a fine yellowish silt—were about 2 to 2·5 m. wide and 2·5 m. apart vertically. The upper terrace (Terrace I) showed many signs of its longer exposure to erosion after emergence than the lower one. Just below the latter were the merest traces of about twenty minor terraces. Below these a slightly gullied bank of silt, carrying a few stranded blocks of ice, sloped down 6 m. to a small pool occupying the mouth of a tunnel formed in the projecting ice lobe. Streams following the edge of the ice entered this pool from both sides.

Corresponding features, due presumably to melting, could be traced on the ice lobe that had formed the opposite shore of the lake. The cross-section shows that the surface of the ice lobe had been reduced to what might reasonably be interpreted as a melt platform submerged at the lower (Terrace II) stage. The steepening of the ice slope at the back of this "melt platform" probably represents the little cliff also formed by melting at this stage. No doubt the slope was much steeper and more cliff-like before melting reduced it to its present rounded form.

This change of slope continued into a deep groove where the edge of the glacier became vertical (see Fig. 2, p. 334). The suggestion that the melt platform was formerly backed by a low ice cliff, which was rounded off by melting after the draining of the lake, is not inconsistent with the survival of the ice groove. The surface of the glacier was quite gently inclined and so was fully exposed to the sun. In addition, water melted higher up on the glacier surface and, running down

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